
FINAL PROGRESS REPORT DECEMBER 2003

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PROJECT: TEAM ORIENTED ROBOTIC EXPLORATION TASK ON SCORPION AND K9 PLATFORMS
GRANT: NCC2-1336

1. SUMMARY

This final report describes the achievements that have been made in the project over the complete period of performance. The technical progress highlights the different areas of work in terms of Progress in Mechatronics, Sensor integration, Software Development, User Interfaces, Behavior Development and Experimental Results and System Testing. The different areas are:

- Mechatronics (1)
- Sensor Integration (3)
- Software development (4)
- Experimental results and Basic System Testing (5)
- Behaviours Development and Advanced System Testing (8)
- User Interface and Wireless Communication (12)

2. MECHATRONICS

The most challenging parts of a walking robot are the legs (figure 2). The leg design presented here provides 3 degrees of freedom, which is the minimum needed for a robust, outdoor walking robot, e.g. it provides the possibility to walk omnidirectional in narrow environments. The leg consist of a thoracical joint for protraction and retraction, a basalar joint for elevation and depression and a distal joint for extension and flexion of the leg (see also figure 2). The joints are actuated by standard 6 Watt 24V DC-Motors with high gear transmission ratio for sufficient lifting capacity.

An important constraint in the development was the outdoor capability. Therefore a good trade-off between making the leg as light as possible to improve its lifting capacity and shielding it against the environmental influences like dust and water had to be found.

We achieved a weight of 950 grams and a weight to lifting-capacity ratio of 1:8. This is a prerequisite to walk up steep rises or to walk over obstacles higher than the robot itself. Another challenge was to integrate compliant elements in the design in order to make the robot robust enough to withstand the mechanical stress in an outdoor terrain.

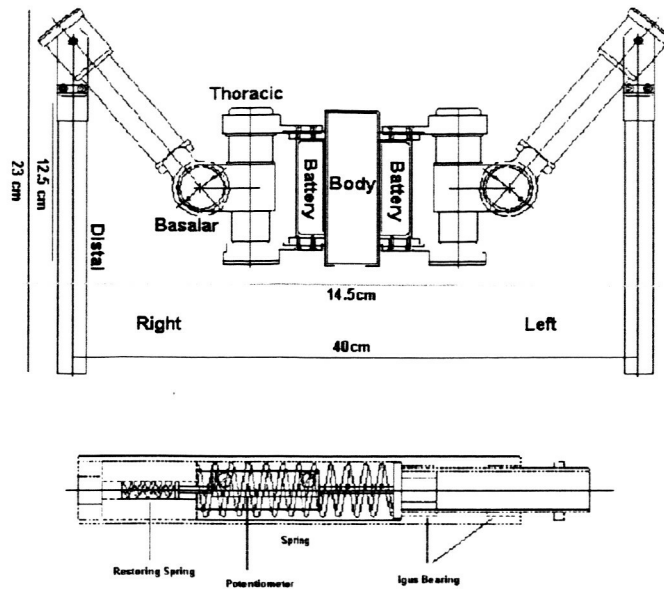


Figure 1: The mechanical design of the Scorpion legs. This front view of the robot shows left and right side legs with the body in the center. Each leg consists of 3 parts: 1) thoracic joint, 2) basalar joint and 3) distal joint. (right) The distal segment contains a spring damped compliant element with a built in potentiometer to measure contact and load on individual legs. The most energy absorbing part in our design is a spring element integrated in the distal segment of the leg (see figure 2). The distal spring element is also used for measuring the ground contact force by an integrated linear potentiometer. From this the robot can compute the load for each leg.

Plug and Play legs have been developed that can be changed by simply loosening 2 screws. The software recognizes the replacement leg autonomously and adjusts the new leg automatically. Battery replacement can be done on-line by plugging in the power cord, changing the battery pack and unplugging the power cord. The system will then continue to work. Advantage of this approach is: no turning off of the system and restarting after battery replacement. A scanning (left right movement of approx. 45 degrees) Ultrasound sensor has been integrated in the front of the system for obstacle detection/avoidance.



Figure 2: The Scorpion scanning Ultrasound sensor in the front of the system.

3. SENSOR INTEGRATION

The robot is equipped with the following proprioceptive sensors:

- Motor Encoders for each motor to measure the relative joint angle
- Hall-Effect Motor Current Sensors for each motor
- The analog load/pressure sensor in each the foot tip
- The Power-Management sensors, providing current battery voltage and current power drain
- Three dimensional inclinometers (pitch, roll and yaw)

The following exteroceptive sensors are integrated:

- Ultrasound distance sensor for obstacle avoidance
- Compass sensor for heading control
- Contact/pressure sensors at the foot tip

It is important to note that the legs itself can be used as exteroceptive sensors. One can use the current sensors of the joint motors during the movement as a tactile sensor during movement. In order to allow an operator to communicate with the robot or to take data samples during a test run, the robot is equipped with an wireless 28K Baud bi-directional communication link and a PAL CCD Camera with a 5GHz video/audio link for video transmission. So it is possible to use the robot as a semiautonomous system.

The Operator can control it via high-level commands like walk forward, left, right, go up, go down, move sideward, turn etc. To supervise the system all relevant sensor data is send back from the robot to the operator.

4. SOFTWARE DEVELOPMENT

The software architecture (14) is based on two approaches to robust and flexible real world locomotion in biological systems, which seem to be contradictory at first sight. These are the Central Pattern Generator (CPG) model and the pure reflex driven approach (1, 6, 7).

A CPG is able to produce a rhythmic motor pattern even in the complete absence of sensory feedback. The general model of a CPG has been identified in nearly every species even though the specific instantiations vary among the species to reflect the individual kinematical characteristics in the animals.

The idea seems to be very promising as a concept to stabilize locomotion in kinematically complex robotic systems, see figure 3 and 4. As it resembles the divide and conquer strategies that are reflected in nearly all solutions to complex control problems (4).

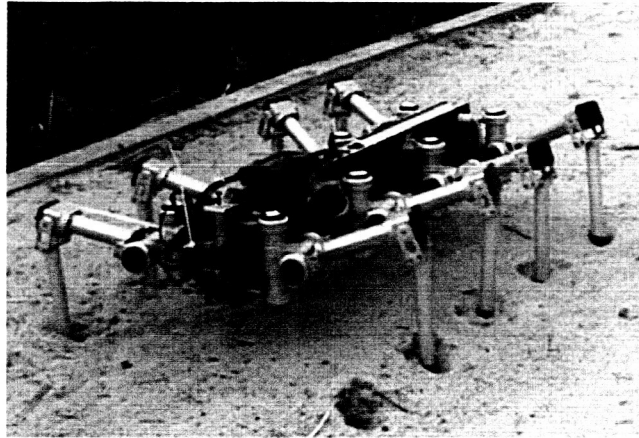


Figure 3: The scorpion robot during an autonomous exploration into a sand bed. The beach like sand bed was 3m wide and 9m long. The robots feet penetrated the sand for aprox. 3-5cm. A reflex mechanism helped to overcome the obstacle.

Another model for the support of robust locomotion is also provided by evolution in the animal kingdom. This is the concept of reflex based control. A reflex can be viewed as a closed loop control system with fixed input/output characteristics. In some animals, like the locust, this concept is said to actually perform all of the locomotion control and no further levels of control, like the CPG, are involved.

Whether or not complex motion control can be achieved only via reflex systems is subject to further discussion, however, the concept of a set of fixed wired reactions to sensory stimuli is of high interest to roboticists who aim to gain stability in the systems locomotion.

The design of the control architecture described here was thus driven by these two concepts. The CPG approach appeared to be interesting to generate rhythmic walking patterns which can be implemented computationally efficient, while the reflex driven approach seemed to provide a simple way to stabilize these walking patterns by providing 1) a set of fixed situation-reactions rules to external disturbances and 2) as a way to bias leg coordination among multiple independent legs.

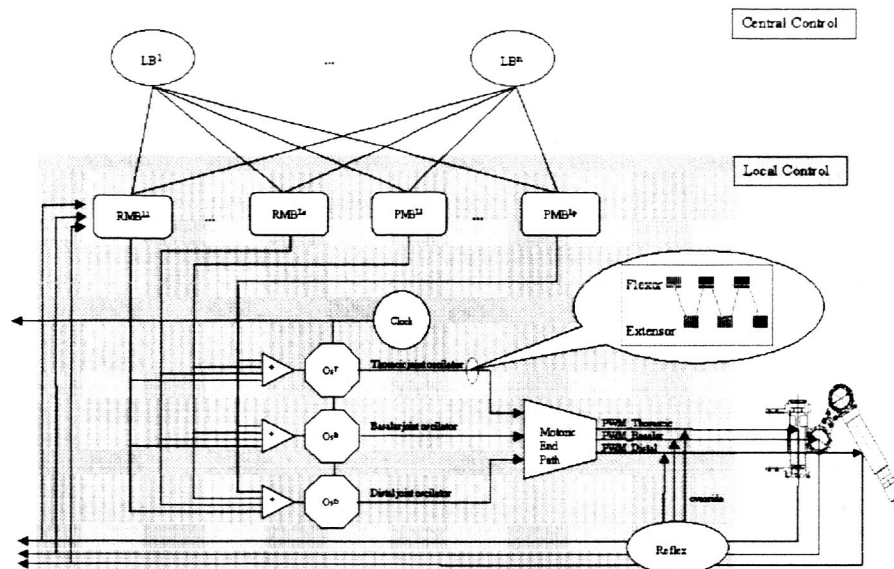


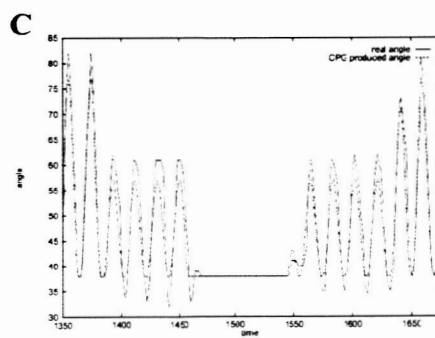
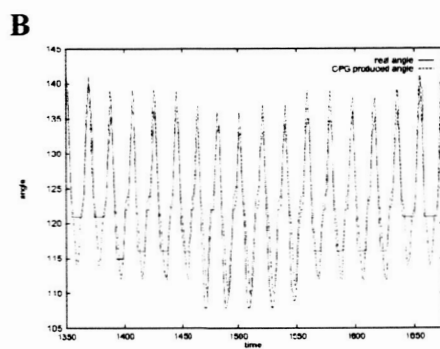
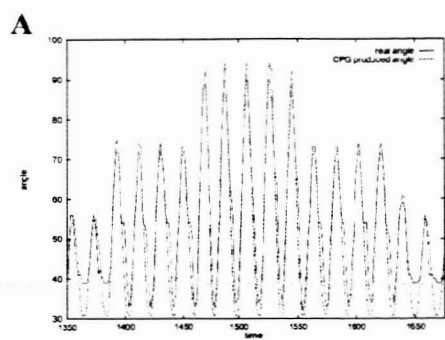
Figure 4: The overall architecture for low level actuation is depicted here.

On the global level (light gray area) we have implemented Locomotion Behaviours (LB's), typically (Forward, Backward and Lateral locomotion). These global behaviours are connected to all local leg controllers and activate (with continuous strength) the local (per leg) motion behaviours. At the same time they implement the inter leg phase relation by setting/resetting the local clocks. The local level (dark gray area) implements Rhythmic Motion Behaviours (RMB's) and Postural Motion Behaviours (PMB's). These behaviours simultaneously influence the amplitude and frequency (see figure 4 and 5) parameters of three oscillating networks (OS^T , OS^B and OS^D). The oscillators are connected to a common clock which is used for local and global (in relation to other legs) synchronization purposes. The oscillators output is a rhythmic, alternating flexor and extensor, stimulation signal (see callout box in figure 4) which is implemented as splined sine waves. This activation signal represents the desired behavioural locomotion, which is translated into PWM signals via the motoric end path. Inline with the output of the motoric end path are a set of perturbation specific reflexes, which are implemented as 'watchdogs'. They override the signals on the end path with precompiled activation signals if the sensor information from the physical joints meets a set of defined criteria.

5. EXPERIMENTAL RESULTS AND BASIC SYSTEM TESTING

This approach was implemented using inter leg coordination data as observed in real scorpions and successfully tested on our 'SCORPION' robot. In the figures 5 A through C, data of the performance of one leg is shown. The solid line is the real angle of the leg, measured with the motor encoders. The angle for the distal and the basilar joints increases during elevation, while the angle for the thoracic joint increases during protraction. The frequency was set to 1.3 Hz (19 time units on the x-axis). The data was taken every 1/25 sec. and the curves are directly computed from the raw data. The mean starting position is at 37 degree for the thoracic joint, 121 degree for the basilar joint, and ca. 30 degree for the distal joint. At first only a local FORWARD behaviour is stimulated (until $t = 1375$), then the LATERAL behaviour is activated simultaneously. Because of the equal strength of the activation the system now tries to walk forward as well as laterally, which results in a diagonal walking.

Approximately at time $t = 1460$ the activation of the FORWARD behaviour is set to 0 which leaves only the LATERAL behaviour to influence the oscillator networks (see figure 4 and figure 5 A-C). Thus the system walks laterally, which can be observed from the data as the amplitude of the thoracic joint is 0 while the basilar and especially the distal joint perform large amplitude oscillations. Subsequently the described process is reversed.



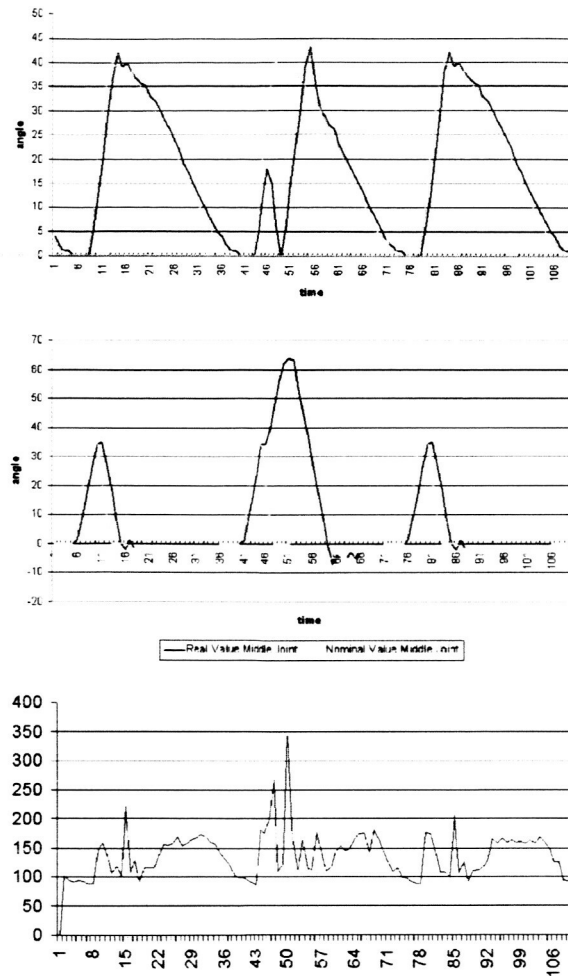


Figure 5: Traces A through C show the movements of the thoracic (A), the basalar (B) and the distal (C) joints during a transition from forward walking (pure FORWARD activation), to diagonal (equal activation of FORWARD and LATERAL), to lateral walking (pure LATERAL activation) and back to forward walking. See figure 4 for the pathways of activation.

A reflex initiated at a leg during a course through a rock bed. The current in the thoracic joint (Trace C) increased as a result of the obstacle blocking the way. At the same time the angular displacement error (Trace A) in the thoracic joint increased, indicating an exception in the regular swing cycle. As a result of these factors the basalar joint controller initiated the reflex (Trace B) that elevated the leg further, thereby overcoming the obstacle.

The approach described here for the generation of rhythmic motion deals very well with plain surfaces without obstacles. However, in the case of uneven ground poor results would be expected.

Our approach to deal with uneven terrain was to implement a set of reflexes in parallel to the motor end path (see figure 5, right side), which override, for a short and predefined period of time, the rhythmic activity of the oscillators. E.g. (see figure 5, right side), if the current values of the thoracic joint increase steep and a significant angular displacement error is detected at the same time, it is assumed that the 'planned' trajectory is blocked. This triggers a reflex, which moves the leg backward and upward (via joint activity in the thoracic and basalar joints) and then forward at max. speed. This reflex is illustrated in figure 5, right side, (start point at $t = 46$, stop at $t = 58$). The reaction-time of the reflexes are as fast as $1/100\text{sec}$. because they are directly in

line with the motor control signals. The 3 pictures also illustrate how fast the motor controller returns back to the pattern given by the oscillator, after the reflex is no longer active. It is important to notice that the action of the reflex does in fact sit right on top of the ongoing rhythmic activity. As can be seen in Figure 5 (right hand traces) the oscillatory activity is always present in the background (light, grey lines), as soon as the reflex is terminated, the locomotion returns to the oscillation.

6. BEHAVIOURS DEVELOPMENT AND ADVANCED SYSTEM TESTING

Direct new technical developments are reported in the following sections with respect to behaviour development. We have been focused to prepare the system for Testing on the SWRI Test site. In order to be able to perform as much testing as possible we have worked on 2 main aspects:

New behaviours have been implemented that allow the system to overcome more and difficult obstacles.

- A behaviour to attach to branches and similar structures has been implemented (see figure 6)

- A behaviour to slide on a branch, after having attached to it has been implemented (see figure 6)



Figure 6: The Scorpion Robot attaching to a structure and then using the structure to overcome a ditch by sliding on the structure.

A behaviour to push pull with front and hind legs while holding on to a branch or similar structure has been implemented to overcome very wide ditches (multiple meters) with a tree or similar structure as a bridge. (figure 7)

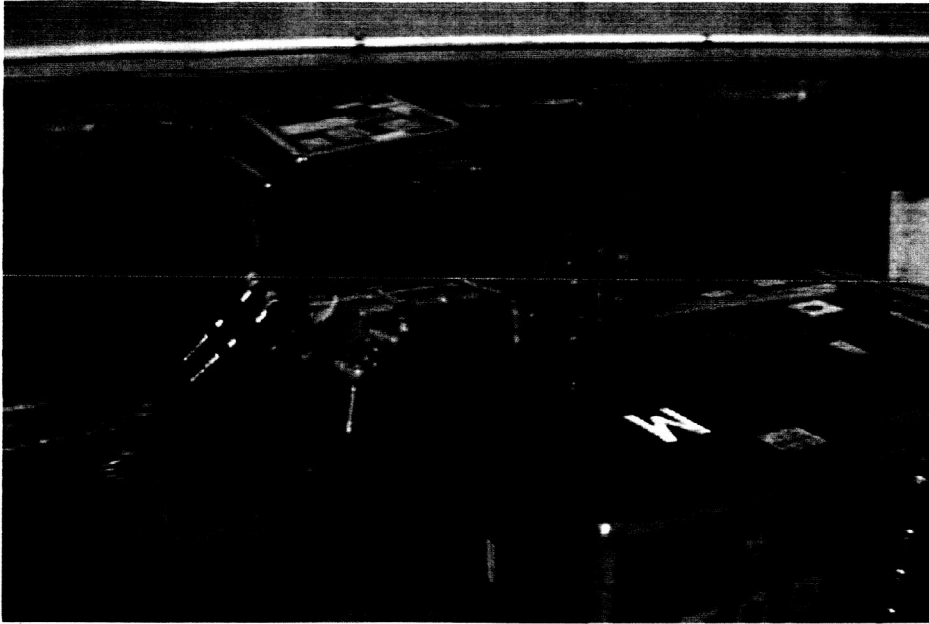


Figure 7: The Scorpion using its front/hind legs to pull/push to overcome a natural bridge over a ditch.

A behaviour to lay down/ stretch out the front legs has been implemented to overcome small ditches that are wider than the robot is long and with no structural features (like natural bridge).

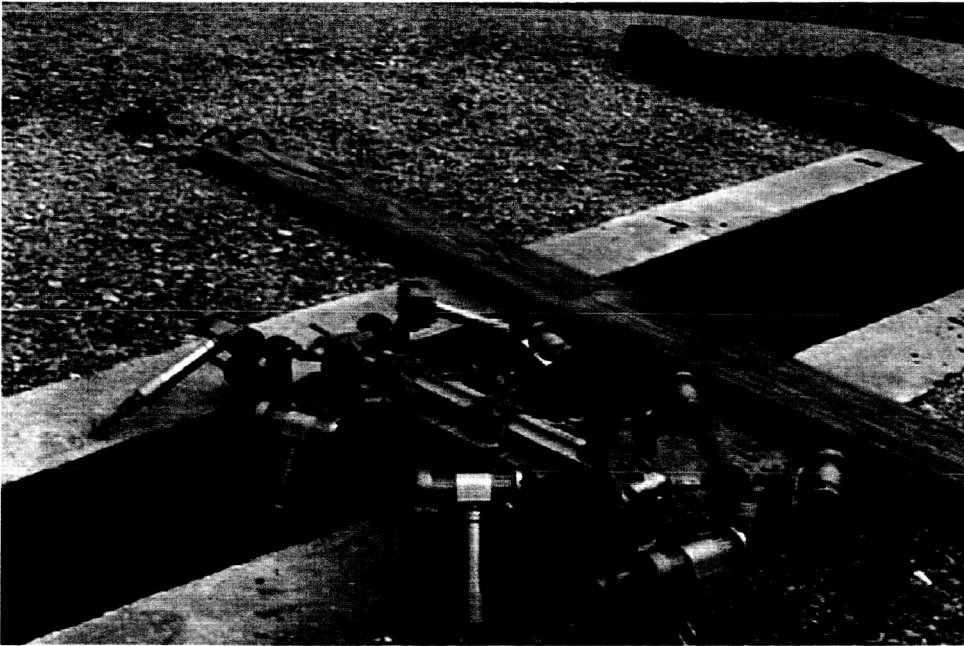


Figure 8: The Scorpion robot using its front legs to overcome ditches without structural features like natural bridge.

A roll over behaviour has been implemented. This behaviour becomes active if the system is laying on its back. Instead of rolling around it will simply continue to walk on its back by inverting the direction of its legs.

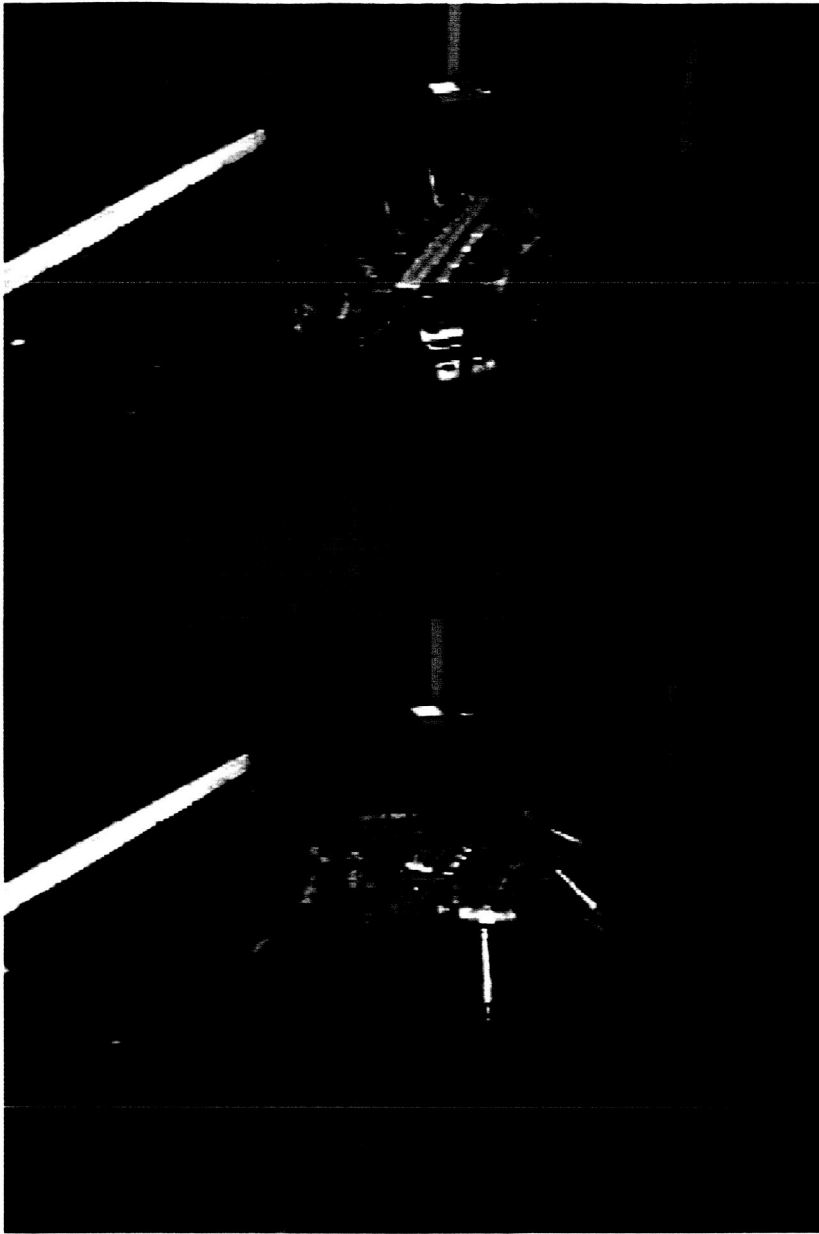


Figure 9: The Scorpion robot inverting the direction of its legs after having toppled over and laying on its back. It can then continue to walk/operate normally.

A behaviour has been implanted to use one of the 8 legs to grab objects (e.g. a wooden bar) and to carry it away by using only 7 legs for walking.

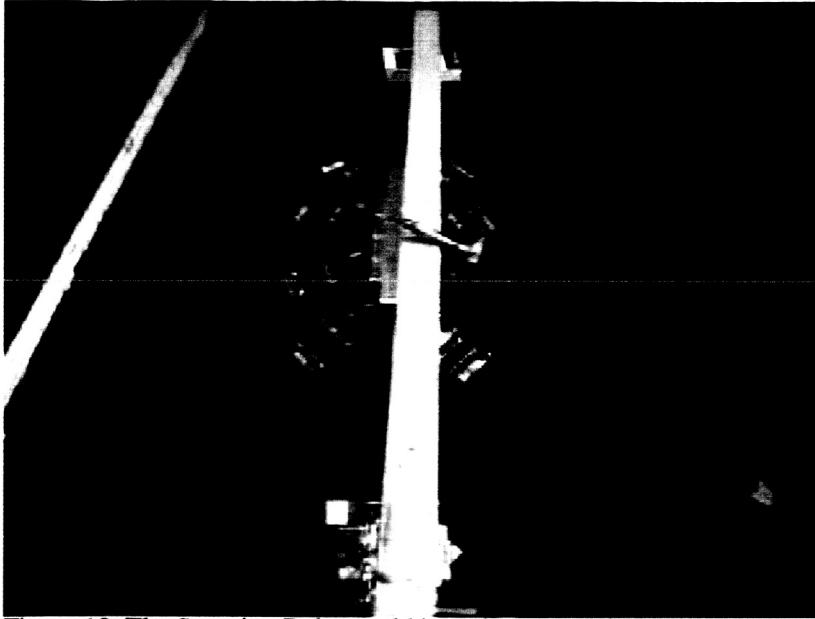


Figure 10: The Scorpion Robot grabbing a board (4.5. kg)

A behaviour has been implemented to compensate for a missing or otherwise used leg (other than walking).



Figure 11: The Scorpion robot holding a board (2.5 kg) while walking over an obstacles (height of the obstacle 25cm).

7. USER INTERFACE

The following paragraph describes the Scorpion User Interface and PC control center for wireless communication with the robot.

At the top left corner of figure 11 is the **BasicMovements** area, which holds various buttons for sending movement commands to the SCORPION. At the top right corner the **DataFlow** is located, which shows you various data sent to the SCORPION and especially sent by the SCORPION. At the bottom of the SCI you should see some graphics. These are dynamic **Visualisations** for incoming SCORPION data. Currently these visualisations include an artificial horizon (like in aircrafts), an ultrasonic obstacle detector, and a compass. The obstacle detector will indicate nearby obstacles in front of the SCORPION, while the artificial horizon shows you the roll and pitch status of the SCORPION.

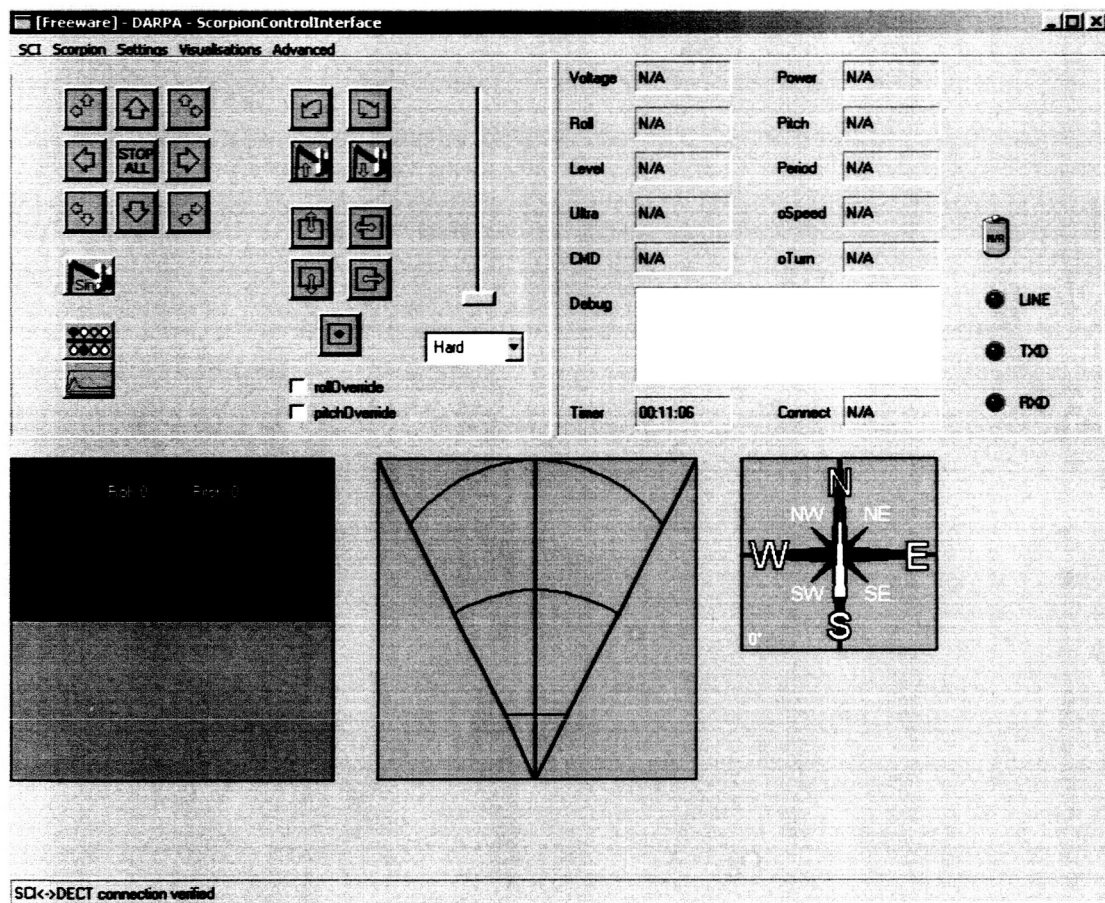


Figure 11: The Scorpion GUI- User Interface for PC control and wireless communication of / with the system.

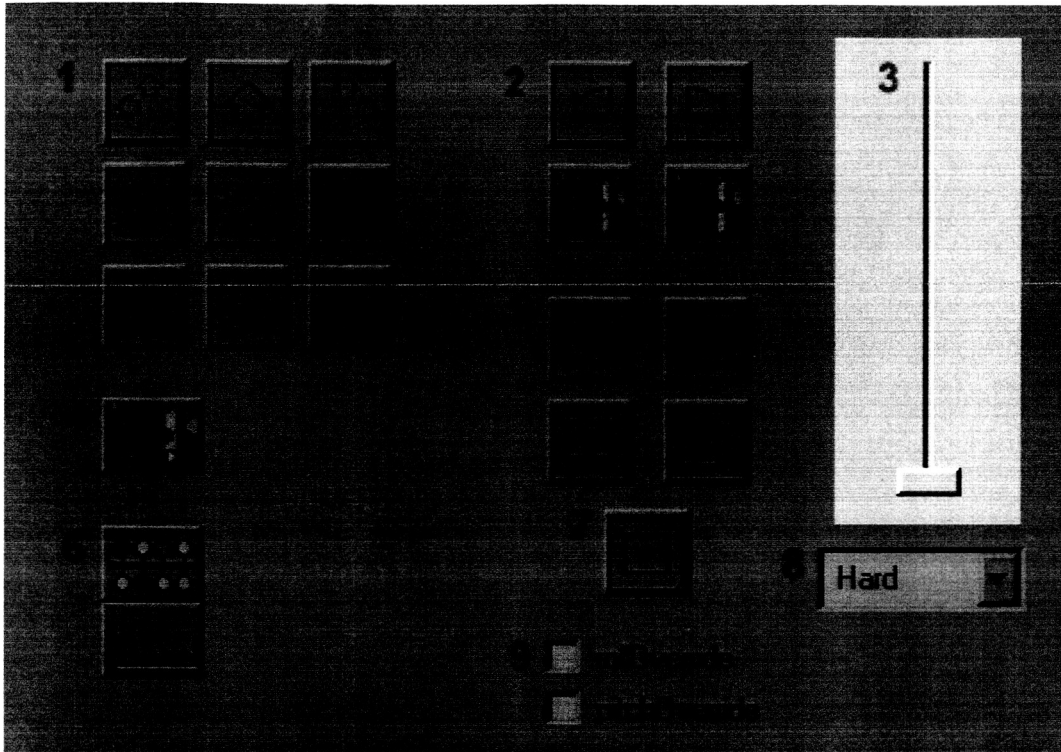


Figure 12: The movement Behaviour panel to control higher level Behaviours of the Scorpion Robot.

Movement Behaviour

When the SCORPION is commanded in different directions, the SCORPION will not change directions immediately from one second to the other. We designed the movements with some amplifier that shall enable the SCORPION to perform a smooth direction change. For example, when already turning left and now sending out a turn right command, the SCORPION will first only decrease turning to the left. After receiving enough commands to turn right, the amplifier will change and the SCORPION will now start to slowly turn right. The more turn right commands you send, the more the SCORPION will react. This behaviour is used in many movements, but not in all of them (e.g. changing the height of the torso).

Future issues.

We have prepared a new proposal to the NASA IS program. This proposal aims to continue the work on team robot interaction and extends the current state of the art in robot coordination and cooperation. The proposal is titled: Extension of the "Scorpion" robot capabilities to cooperative exploration of rough terrains and steep cliffs'